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HEAT TRANSFER MEASUREMENTS OF SAFETY APPAREL FABRICS.(U)
JAN 78 A M STOLL, M A CHIANTA

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HEAT TRANSFER MEASUREMENTS OF SAFETY APPAREL FABRICS.

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Twenty-one fabrics of possible use in thermal protection were submitted for evaluation of their heat transmission characteristics. Measurements of heat transfer were made on exposure of the fabrics to flame contact and to radiation at flux levels of practical interest. The results are summarized in Table I and discussed with respect to their use in design of improved thermal protection clothing.

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HEAT TRANSFER MEASUREMENTS OF SAFETY APPAREL FABRICS

INTRODUCTION

In an effort to acquire systematic data on heat transfer characterics of experimental and off-the-shelf safety apparel fabrics, the present investigation was undertaken. It utilizes the philosophy and methodology described in detail earlier (1) and should be considered in the light of the discussions contained in this reference (Appendix I).

MATERIALS AND METHODS

The materials used are 21 specimens submitted by Cotton Incorporated for comparative study. All are identified and described in Table I wherein the measured heat transmission characteristics are summarized.

The method for assessing heat transmission in each instance consists of covering an instrumented skin simulant (2) with the fabric specimen and exposing the section to a square wave pulse of heat from a Meker burner flame or from a radiant source under controlled conditions. The temperature rise is measured continuously from the beginning to the end of each exposure and the resultant data interpreted in terms of physiological effects of pain and blister as described in Reference 1, (Appendix I). In the instance of flame contact, the flame temperature is approximately 1200^{o}C at a flux level of about 1.3 cal/cm^2 sec, commensurate with that of large-scale fires. In the instance of radiant exposures, the flux used is equivalent to that from a blackbody at approximately 1900^{o}C at a flux level of about 5 cal/cm^2 sec incident on the fabric. As noted in Reference 1, few commonly encountered flames exceed 1200^{o}C (ca. 2200^{o}F), while radiation exposures may vary from virtually 0 to intensities of thermonuclear magnitudes. A source temperature of 1900^{o}C was selected to provide practical extremes of spectral distribution such as are possible in graphitizing

TABLE I. HEAT TRANSMISSION CHARACTERISTICS ON EXPOSURE TO FLAME AND TO RADIATION

Fabric					Flame Contact (at 1200 °C)					Radiation (T_b** = 1900 °C)					
						Protection time (sec)									
					ΔTss* °C/H	at 1 cal/cm² sec		at 1.3 cal/cm² sec		ΔTss* °C/H at		Protection at 1 cal/cm² sec		Irradiance (cal/cm² sec) Tolerable to Pain Endpoint	
Log # 375	Description	Weight oz/yd²	Thickness mm	Color	at 3 sec	Time to Pain	Time to Blister	Time to Pain	Time to Blister	2 sec	3 sec	Time to Pain (sec)	Time to Blister (sec)	for 1 sec	for 3 sec
a 1	Nomex Suiting	5.8	0.354	navy blue	16.56	1.6	3.9	1.2	2.7	4.99	7.48	4.8	12.0	3.3	1.4
UMA/F e 2	Cotton Flannel (Fireaway 2S)	4.2	0.434	patterned pink on white	16.11	1.7	4.0	1.2	2.8	5.39	8.08	4.3	10.6	3.0	1.3
FR/CRF/MCS f 3	Cotton Mt. Cloth Shirting (FR/CRF)	7.2	0.449	yellow	15.92	1.8	4.1	1.2	2.8	4.66	6.99	5.2	13.1	3.5	1.5
b 4	Nomex Duck Turnout Coat	7.7	0.501	navy blue	15.81	1.8	4.1	1.2	2.8	4.80	7.20	5.0	12.4	3.4	1.5
32/ST/RES s 5	Cotton Supertwill Resin finished #32	9.6	0.510	navy blue	14.20	2.0	5.0	1.4	3.4	4.43	6.64	5.5	14.0	3.7	1.6
29/3/C/LF m 6	Cotton Mt. Cloth 3S Permafresh #29	9.2	0.582	tan	14.12	2.1	5.0	1.4	3.4	3.93	5.89	6.5	16.6	4.1	1.8
32/MC/RES n 7	Cotton Mt. Cloth Resin finished #32	9.2	0.563	green	14.04	2.1	5.0	1.4	3.4	4.15	6.22	6.0	15.5	3.9	1.7
32/ST/SANF r 8	Cotton Super twill FR/Sanforized #32	9.1	0.556	navy blue	13.43	2.2	5.1	1.5	3.8	4.59	6.88	5.3	11.1	3.5	1.6
32/T/RES o 9	Cotton Twill Resin finished #32	10.4	0.657	green	12.96	2.3	5.5	1.6	3.8	4.25	6.37	6.0	15.1	3.8	1.7
32/T/SANF p 10	Cotton Twill FR/Sanforized #32	10.0	0.664	green	12.81	2.3	5.6	1.6	3.8	4.53	6.79	5.4	13.6	3.6	1.6
32/S/RES j 11	Cotton Sateen Resin finished #32	10.3	0.643	green	12.73	2.3	5.6	1.6	3.8	4.31	6.46	5.8	14.6	3.8	1.7
THPOH/NH_3 h 12	Cotton Sateen Trial #15	9.5	0.649	green	12.37	2.4	5.9	1.7	4.1	3.80	5.70	6.9	17.8	4.3	1.9
EP/B/SANF g 13	Cotton Carded Sateen Reeves production	9.7	0.630	yellow	12.20	2.5	6.1	1.7	4.1	4.26	6.39	5.9	15.0	3.8	1.7
32/S/SANF k 14	Cotton Sateen FR/Sanforized #32	9.7	0.678	green	11.97	2.5	6.2	1.8	4.2	4.01	6.01	6.4	16.3	4.1	1.8
FR/SANF/D l 15	Cotton Mt. Cloth THO/Permafresh #29	9.2	0.568	navy blue	11.93	2.5	6.2	1.8	4.2	4.42	6.63	5.6	14.2	3.7	1.6
c 16	Kynol Turnout coat fabric	8.1	0.535	gold	11.60	2.6	6.6	1.8	4.2	4.23	6.34	5.9	15.2	3.8	1.7
Sample 2A t 17	Cotton Whipcord Reeves production	10.0	0.750	sage green	11.54	2.7	6.5	1.9	4.5	3.77	5.65	7.0	17.9	4.3	1.9
31/T/CRF q 18	Cotton Twill Trial #31	10.6	0.659	navy blue	11.16	2.8	6.9	2.0	4.7	4.23	6.34	5.9	15.1	3.8	1.7
31/S/CRF3 i 19	Cotton Sateen Trial #31	10.3	0.663	navy blue	10.52	3.1	7.5	2.1	5.1	4.12	6.18	6.1	15.8	3.9	1.7
Sample A u 20	Cotton Whipcord Reeves production	11.7	0.740	sage green	10.47	3.1	7.5	2.1	5.1	3.56	5.34	7.5	19.2	4.6	2.0
d 21	Cotton denim (Sanforized)	14.1	0.813	navy blue	10.29	3.1	7.6	2.2	5.3	4.01	6.01	6.2	16.3	4.1	1.8

* ΔTss = Temperature rise in simulated skin in °C per unit flux (H) in cal/cm² sec

** T_b = Blackbody temperature of radiant source

and open hearth furnaces. This radiation peaks at 1.5μ and contains considerable visible radiation but much less than that of thermonuclear pulses. This means that some of the incident radiation is reflected by the fabrics, in general, the lighter the color, the greater the reflectance.

EXPERIMENTAL RESULTS

Table I summarizes the experimental results. Each temperature rise value listed is the average of at least three exposures in which the difference from the mean of any simple reading is not greater than ±5%; the overall accuracy for the flame exposures is ±2.9% and for the radiation exposure, ±2.0%. Differences in thickness from site to site, and type of construction (e.g., ribbed), contribute to experimental variation and may account for the occasional large single reading difference from the mean.

The data in Table I are arranged in the order of increasing protective capacity with respect to flame contact so that the first column of the Flame Contact section shows the decreasing order of temperature rise measured in the skin simulant. This order does not hold for the Radiation section because the net effect of radiant exposures depends greatly upon the spectral characteristics of the source and the optical properties of the fabric. In both instances, flame contact and radiant exposure, the time to pain and to blister at a flux of 1 cal/cm^2 sec have been noted. This information is obtained directly from Figure 2 of Appendix I by looking up the Tolerance Time corresponding to each ΔTss, ^{o}C/H at 3 sec, on the Pain and the Blister curves. For flame contact an additional set of data is shown for a flux of 1.3 cal/cm^2 sec, the actual level of the experimental source and a common figure for fuel fires. These data are obtained by multiplying the ΔTss, ^{o}C/H, by 1.3 and again referring to the Pain and Blister parameters of Figure 2, Appendix I.

In the instance of radiation exposures, in addition to time to pain and to blister at 1 cal/cm^2 sec, the radiant flux tolerable for 1 sec and for 3 sec

without pain is shown. These data are derived by reference to the Figure 2, Appendix I, pain curve: At a Tolerance Time of 1 sec, the corresponding ΔTss measured at 3 seconds is $24.4^{o}C$; by construction (3) the temperature rise per unit flux at 3 sec is $36.2^{o}C$, therefore, $24.4 \div 36.2 = 0.674$ cal/cm^2 sec, the heat absorption rate to produce pain in 1 second. Similarly, at 3 sec, ΔTss in 3 sec = $10.7 \div 36.2^{o}C/H = 0.296$ cal/cm^2 sec, to produce pain in 3 seconds. Then, to find the tolerable flux under the fabric: the measured ΔTss in 3 sec $\div$ 36.2 = experimental heat absorption rate; 0.674 $\div$ experimental heat absorption rate = tolerable flux for 1 sec and 0.296 $\div$ experimental rate = tolerable flux for 3 seconds. Within reasonable limits, this system can be applied to estimate tolerable irradiances at other exposure times as well.

Considering each fabric in comparison with the others, certain generalizations and exceptions come to light. In general, the protective capacity as estimated by the diminution in heat transfer reflected in decreasing ΔTss in flame contact follows most closely the increase in thickness of the fabrics. The correlation with weight is somewhat less good and serves to emphasize the fact that heat transfer depends on both the mass interposed between flame and receiver and the interstices of air pockets created by the fabric geometry. The one notable exception in sequential correlation is the Kynol fabric which ranks 16th whereas it might be expected to rank about 5th on the basis of either weight or thickness. The Nomex suiting, being the thinnest of all though not the lightest in weight, shows the least protective capacity while the Sanforized cotton denim, the thickest and heaviest fabric, shows the most.

The Radiation section requires individual consideration of each fabric because of the effect of color, reflectance and transmittance properties which have not been measured in these fabrics. For instance, the Nomex suiting is now reversed in ranking with the cotton flannel, showing a lower temperature rise

than the flannel which is thicker but lighter in weight. Since the Nomex is navy blue and the cotton is pink patterned on white, the difference cannot be ascribed to differences in reflectance but is undoubtedly due to higher transmittance of the cotton fabric together with a lower conductivity of the Nomex. Also, the denim fabric (d21) is not the best in these exposures but has yielded place to the next lighter in weight, cotton whipcord (u20), which is sage green rather than navy blue, showing the effect of greater reflectance and possibly lower transmittance as well. Looking at the protection against pain afforded by any of the fabrics, this time varies between 4.3 and 7.5 seconds as compared with 1.6 and 3.1 seconds in flame contact at the same flux level; protection against blister varies between 10.6 and 19.2 seconds as compared with 3.9 and 7.6 seconds in flame contact. On the other hand, the data in the last two columns of the chart indicate that pain is experienced in 1 second at a radiant flux of 3.0 to 4.6 cal/cm^2 sec and in 3 seconds at levels of 1.3 to 2.0 cal/cm^2 second. The latter flux levels are not unusually high for radiation at close proximity to large conflagrations.

DISCUSSION

In using these data to assess the merit of any fabric in a particular application, it is necessary to bear in mind that the data refer to the circumstances in which the fabric is in good contact with the skin, no ignition occurs, the exposure begins and ends abruptly and the assembly is permitted to cool under normal ambient conditions. Any pre- or post- exposure heating invalidates the protection time prediction. Obviously there are fabric characteristics other than weight, thickness and color which affect heat transmission that are not considered here, e.g., air permeability, nap, and yarn twist. In designing a fabric for a specific application all these features must be taken into account and may be systematically varied to provide the desired effect. Therefore, the

present data should be considered to be only an assessment of comparative values of the heat transmission of these fabrics as they are and not as they might be if all were of comparable weight, thickness and construction.

We have been asked to consider the present data as they might bear upon heat transmission due to splashing with molten metal. To this end Reference 4 was provided and consulted. While not specifically identified as such, it appears that some of the fabrics used in that study are the same as those in the present investigation. These are cited in Table II.

There may be others which are the same but not readily identifiable. In any event, because the incident energy was not applied in a square wave pattern in the molten metal study, as the authors note, it is not possible to estimate the amount of skin protection provided. However, the onset of heat exposure was abrupt and the initial heat flux reaching the "skin" was measured. Therefore, it is possible to determine which fabrics might provide enough protection to prevent blistering even though a definite determination cannot be made because of the uncertainties introduced by additional heating after the peak flux.

To make this assessment the data in column 5 of Table II is referred to the Tolerance Time Chart (Figure 1, Appendix I, or Figure 16, Reference 4). The energy noted is taken from Reference 4 (Table II and Figures cited) and is the maximum flux measured at the "skin" surface during the molten metal exposure. Column 6 presents the exposure time at which peak flux occurred; column 7 gives the total time for which the flux remained above about 0.05 cal/cm^2 sec as estimated from the Figures cited in column 4; column 8 shows the time to blister if the heat pulse were a square wave at the level of the maximum flux measured. Comparing columns 6 and 8 only, none of the fabrics are indicated as definitely inadequate since the peak time in each instance is lower than the time to blister at that flux. However, with only one fabric, the Nomex Duck (SRI #6, NADC #375 b4)

Table II. Molten Metal Exposure Data on Comparable Fabrics

Fabric			Protective Capacity - Blister Parameter				
SRI* #	NADC #	Description	SRI* Fig. #	Maximum Flux cal/cm^2sec	Maximum Flux Time (sec)	Time (sec) above 0.05 cal/cm^2sec	Time (sec) to blister @ max. flux
4	f 3	Mt. Cloth Shirting	7	0.80	0.62	4.2	1.8
6	b 4	Nomex Duck	9	0.57	0.50	1.8	2.9
7	c 16	Kynol	10	0.60	0.65	>5	2.7
9	a 1	Nomex Suiting	12	0.62	0.55	>5	2.5

* SRI = Southern Research Institute (reference 4)

is the total time for which the flux exceeds 0.05 cal/cm^2 sec (1.8 sec) well below that required to produce a blister (2.9 sec). Under these circumstances it is quite possible that the heating experienced during drop-off of the flux might not contribute enough additional damage to produce a blister.

Examination of the other data in Reference 4 reveals that the fabric identified as "Cotton Duck" also gives favorable results in that the peak flux is 0.50 cal/cm^2 sec (Figure 8, Reference 4) at which level a 3.4 second exposure is required to produce a blister and the total elevated flux time is about 2.3 seconds, well below this duration. Again, the additional damage during flux drop-off might not be sufficient to produce a blister. Examination of the remaining data in Table II suggests that it is unlikely that any of the other three fabrics would provide adequate protection against blistering because of the prolonged time above 0.05 cal/cm^2 sec (Column 7).

CONCLUSION

From the present data it is concluded that as they stand Cotton Denim (Sanforized), navy blue, 14.1 oz/yd^2, 0.813mm thick, provides the best protection against heat transfer by flame contact; Cotton Whipcord, Reeves Production, sage green, 11.7 oz/yd^2, 0.740mm thick, provides the best protection against radiation corresponding to a blackbody temperature of 1900°C. On the basis of protection against flame contact offered per unit weight or thickness, Kynol Turnout Coat Fabric, 8.1 oz/yd^2, 0.535mm thick, is the only outstanding material, ranking 11 places higher than expected in a field of 21. In the instance of radiation exposure this advantage does not hold, as might be expected from the overriding influence of optical properties.

In summary, the present data provide information of use in the design of fabrics for thermal protection. Knowledge of their heat transfer properties and present construction features can be used to modify the latter. Thus, with due

regard for the mode of heat transfer in operation, whether convective, radiative or conductive, fabric design can be engineered to take advantage of this knowledge to improve protective capacity in specific applications.

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APPENDIX I

Method and Rating System for Evaluation of Thermal Protection

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STOLL, A. M., and M. A. CHIANTA. *Method and rating system for evaluation of thermal protection.* Aerospace Med. 40 (11):1232-1237. 1969.

Thermal protection rating systems for fabrics, based on pain and blister effects in human skin, are considered in terms of: (1) precise evaluations applicable to any known temperature-time pattern, and (2) simple laboratory procedures to provide a universally useful standard rating system. The first system which is more comprehensive is difficult and requires computer operations routinely; the second, described in detail, offers a rating system which is simple, directly related to pain and blister parameters, and may be understood by the uninitiated as well as those knowledgeable in the field.

CONVENIENT METHODS of evaluating the thermal protection capacity of clothing fabrics have been sought by developers and users alike. Most methods in use provide relative data that indicate which of any number of candidate materials is more heat-resistant than others. Two methods, at least, relate these data to protection of living skin[1] and offer a basis of comparison in terms of "critical radiant exposures,"[2] i.e., the product of energy and exposure time required to destroy the clothing or to burn the skin on exposure to thermal radiation pulses simulating nuclear weapons of various potencies. Another method yields a protection index which is the ratio of the energy-time product observed for clothed skin to that of bare skin.[3] None has provided a procedure which is universally applicable for rating fabrics against a physiological standard representative of tissue injury sustained under the fabric without the necessity of making measurements *in vivo*.

The present report discusses a method based upon a tissue injury concept which correlates the observed skin temperature-time history with complete trans-epidermal necrosis[4,5,6] and also proposes a simple method of rating fabrics which could be used as a standard by all laboratories engaged in this work. The procedures to be described utilize the skin simulant described by Maggio[7] but any substance of precisely known thermal properties could be used equally well.

Opinions and conclusions contained in this report are those of the authors. They are not to be construed as necessarily reflecting the views or the endorsement of the Department of the Navy.

BACKGROUND

It is now well known that the severity of a skin burn depends upon elevation of the tissue temperature to an injurious level, i.e., higher than 44°C, and maintenance of the elevation for a time inversely related to the temperature. The rate at which injury proceeds increases logarithmically with a linear increase in skin temperature so that at 50°C damage proceeds at 100 times the rate ensuing at 45°C.[6] Extrapolation of the rate vs. temperature curve indicates that complete trans-epidermal destruction occurs virtually instantaneously at 72°C. Consequently, the range of injury may be delineated as occurring at basal layer temperatures of 44°C to 72°C, sustained at elevated-temperature times varying from, nominally, infinity to zero, respectively. It is understood that this delineation applies to sequences in which the temperature-time pattern is regular, continuous and known, or in which the temperature is known for every instant in time if the pattern is discontinuous or irregular. In actual living skin, temperature-time histories leading to a damage-rate temporal integral of 1.0 in a computer operation such as described in Stoll[8] would then indicate destruction of the skin.

For the purpose of setting up a protection index the system may be adapted to the simulated skin and applied in a similar fashion. In this application the differences between the physical constants of human skin and the skin simulant would be normalized mathematically by substitution of the constants appropriate to the simulant in the equation applicable to the living skin and subsequent adjustment of temperature-rise rates in the two media so that skin destruction is indicated when Ω (symbol for damage[4]) equals 1.0 in either system. This system requires incorporation of a sliding scale factor to accommodate to changes in thermal conductivity which occur more markedly in the living skin than in the simulant because the former is susceptible to blood and tissue fluid shifts which are absent in the inert material of the simulant.

Table I points up some of the similarities and differences between living skin and the simulant. It is a compilation of data from radiation exposures of blackened human skin[6] and theory,[9] and equivalent effects in the simulant.[10] The first column shows the incident

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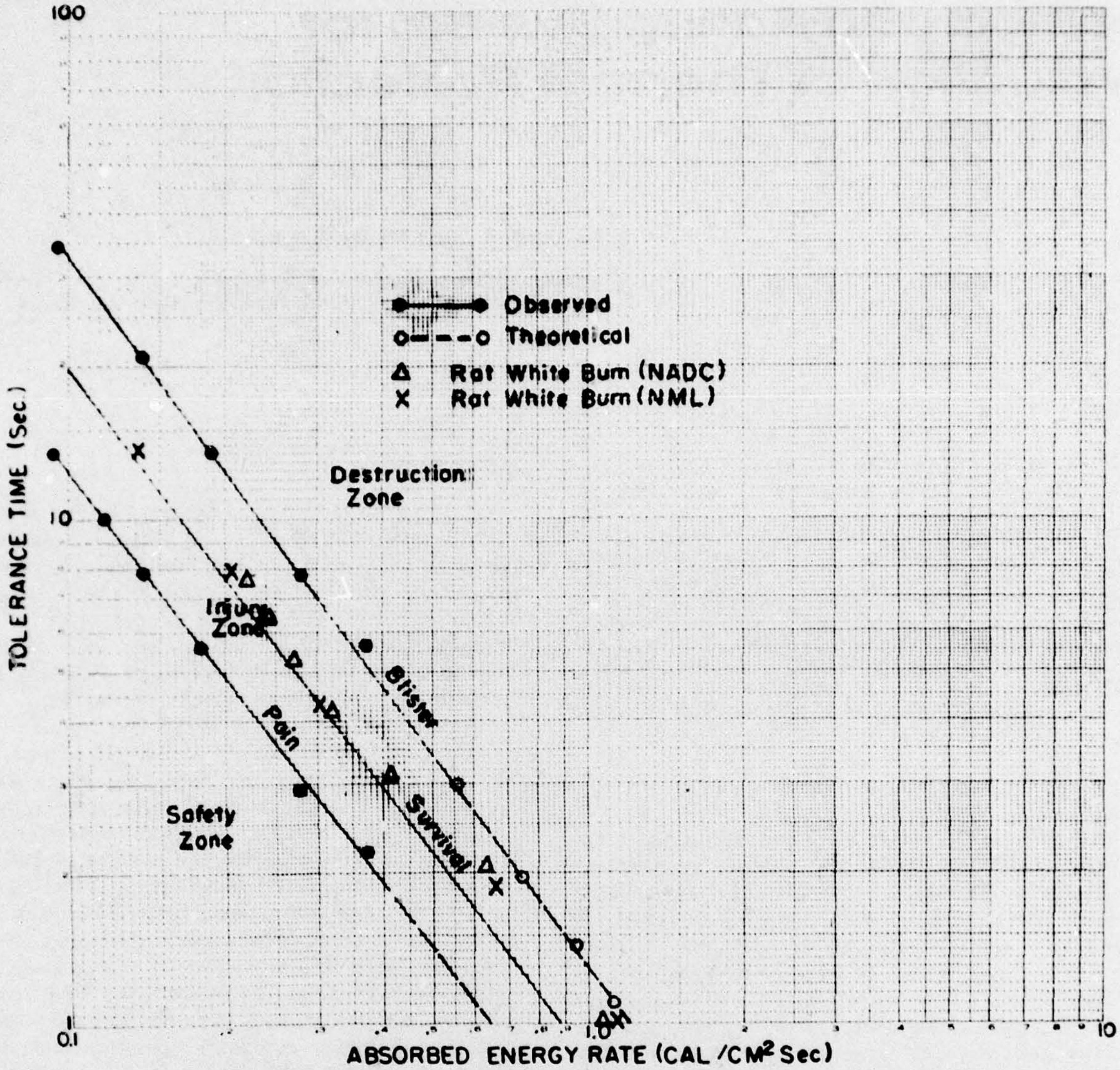

Fig. 1. Human skin tolerance time to absorbed thermal energy delivered in a rectangular heat pulse.

TABLE I. TEMPERATURE RISE IN HUMAN SKIN AND IN SKIN SIMULANT ON ABSORPTION OF THERMAL RADIATION JUST SUFFICIENT TO CAUSE BLISTERING

Heat cal/cm² sec		Exposure Time to burn	Max. Temp. Rise		Max. Temp. Rise		Ratio	Ratio
Incident	Absorbed	(sec)	ΔT_s °C	ΔT_t °C	ΔT_{ss} °C	ΔT_{sd} °C	$\Delta T_{ss}/\Delta T_s$	$\Delta T_{sd}/\Delta T_t$
1.20	1.128	1.08	35.3	29.9	45.4	14.7*	1.285	0.493*
1.00	0.940	1.41	33.5	28.5	43.4	16.0*	1.295	0.561*
0.80	0.752	1.95	31.2	26.9	41.0	17.9*	1.314	0.666*
0.60	0.564	3.0	28.7	25.4	37.8	20.4	1.352	0.804
0.40	0.376	5.6	26.6	24.7	34.6	22.6	1.301	0.914
0.30	0.282	7.8	24.2	22.7	32.4	21.1	1.340	0.929
0.20	0.188	13.4**	22.4	21.4	26.9	19.2	1.202**	0.908
0.15	0.141	20.8**	21.5	20.7	25.1	18.0	1.208**	0.837
0.10	0.094	33.8**	20.4	19.8	21.3	15.1	1.044**	0.762

T_s = Temperature of skin surface.

T_t = Temperature of skin at the basal layer, 80μ beneath the surface.

T_{ss} = *Temperature of simulant surface*

T_{sd} = Temperature of simulant at depth of 500μ beneath the surface.

*Exposures < 3 sec. are too short to permit temp. change at 500μ comparable to that at 80μ.

**Blood flow changes influence surface temp. ratios in exposures > 10 sec.

energy; the second, the absorbed energy; the third, the observed exposure time to produce a minimal blister in the blackened human living skin; and the fourth and fifth respectively, the measured maximum temperature rise at the surface of the skin (ΔT_s), and that calculated for a depth of 80μ beneath the surface, approximating the location of the basal layer (ΔT_t). The next two columns show equivalent data for the skin simulant except that the depth at which the temperature is measured in the simulant is 500μ. The final two columns give the ratios between the temperature rises in the simulant and the skin at the surfaces and at depth, respectively. It is readily seen from the data tagged with an asterisk that exposures less than 3 seconds in duration are too short to permit a temperature change at 500μ in the simulant comparable to that at 80μ in the living skin. The data tagged with a double asterisk indicate the region in which blood flow changes influence the temperatures attained in the living skin and significantly alter the simulant temperature rise ratios. Thus, it is obvious from the figures in the next to last column, that the ratio of temperature rise of the simulant and the skin surface is fairly consistent for short-term exposures but falls off as the exposure time extends beyond about 10 seconds. The difference in the ratio of temperature rise at depth in the skin and in the simulant (last column) is even greater because, in addition to variable conductivity in the skin, the depths at which the temperatures are measured are significantly different. Therefore, this ratio is constant only between about 5 and 20 seconds' exposure time. However, with suitable adjustments a system could be provided wherein temperature-time histories of both skin and simulant may be translated directly into injury integrals. The latter become protection indices on comparison of measurements made under candidate fabrics with a damage scale in which an integral of 1.0 is equal to destruction, less than 1.0, some measure of protection, and greater than 1.0, an increase in burn hazard by virtue of flaming or other exothermic reaction of the simulant cover. Precise as this may be, it is doubtful that so elaborate a system is really desirable as a standard or screening method since it would require multiple observations and computer operations routinely. On the other hand, it might well be suited to analyses of burn hazards in situations where the heating pattern is irregular and live animals could not be used. This development is being pursued as part of a continuing study on thermal injury.

MATERIALS AND METHODS

For the present purpose, a simpler system based on observed data[6] and empirical relationships has been developed for routine use. This system is illustrated in Figure 1 where tolerance times for different levels of thermal energy are plotted on log log coordinates. Pain threshold and mimimal thermal blister paramters derived from earlier work[6] are used as the lower and upper limits of skin injury. In applying these data it is absolutely essential that the heat pulse used be rectangular, for any variation from this shape invalidates the data. Then, for a given intensity of heat absorbed by the skin, the time for which this intensity may be tolerated safely is read to the left of the pain line; reversible injury occurs at coordinates between the pain and blister lines, and irreversible damage to the right of the blister line. The median line shown is drawn through the mid-points between the parameters of pain and blister.

For the benefit of those investigators who may wish to relate these data to comparable observations of white burns, in the anesthetized, depilated white rat, the latter, derived from two different laboratories[11,12] are included in this figure. Both sets of data were normalized by correcting the observed exposure times to those commensurate with an initial skin temperature of 32.5°C, which is the initial temperature of the human skin data (a correction of –0.5°C in the Naval Air Development Center data and +1.5°C in the Naval Material Laboratory data). It is seen that all the points fall to the left of the blister line and to the right of the median between blister and pain. The rat white burn may then be considered as approximating the second degree burn in a human, at least in this range of energy and exposure time. It is noteworthy that within the range of experimental data these points fall approximately on the median line of the human data but approach the blister line in the extrapolated area where the energy absorption rate is high and the tolerance time short. It may be that the human data curves too would skew in a somewhat similar manner if experimental data were available in this region. However, the deviation is not great and the present arrangement errs on the side of safety, if at all, i.e., the tolerance times indicated are shorter than they would be if, indeed, the human data should parallel the rat burn data.

To evaluate a fabric the general procedure consists of exposing it to a rectangular heat pulse in such a manner that the heat passing through it, may be measured with respect to time. When flame contact or convection is the heating mode, the optical properties of the fabric have no bearing on the heat transmission but when radiation is the mode the optical properties are extremely important.[13] For instance, the heat transferred through a particular material of one color on exposure to radiation may be greatly different from that transferred through an identical specimen of different color simply because of differences in reflection and absorption. In any case, the crucial part of the procedure is the establishment of the energy flux absorbed by the skin underneath the fabric. For this purpose the NML skin simulant[7] is very convenient. The fabric is overlaid on the simulant and the temperature rise at a depth of 0.05 cm (500μ) beneath the simulant surface is recorded with respect to time on exposure to the rectangular pulse. Routinely, the temperature rise noted at 3 seconds (2 seconds with high-intensity radiation) has been used as a reference point. Figure 2 shows the tolerance time for human skin related to the observed temperature rise at 3 seconds. Again the three zones of tolerance are delineated by the pain threshold and blister threshold parameters. In using this system the absorbed energy in cal/cm^2 sec may be found simply by dividing

the observed temperature rise by 36.2°C, the rise commensurate with absorption of 1 cal/cm² sec by the bare simulant.[10] Of course, it is not necessary that this specific simulant be used; any similar device calibrated to yield a measurement of the energy absorbed by the skin could be used just as well.

RESULTS AND DISCUSSION

To provide interchangeability of data from different laboratories, a uniform expression is necessary. For this purpose it is suggested that a cover or assembly that restricts the absorbed energy-time coordinates to the area left of the pain line be termed "protective against pain (PAP)-seconds at X incident energy"; that which confines it between the pain and blister lines be termed "protective against blistering (PAB)-seconds at X incident energy"; and that which fails to confine it to the left of the blister line, "non-protective (NP) at X incident energy." For example, if exposure of a given fabric to a rectangular pulse of 1 cal/cm² sec produces a temperature rise of 10°C at 3 seconds in the skin simulant, reference to Figure 2 indicates a tolerance time of 3.2 seconds at the pain threshold parameter and 8.0 seconds at the blister parameter. Similarly, if absorbed energy flux is the quantity measured, then for the same situation this would be 0.276 cal/cm² sec and reference to Figure 1 would indicate the same tolerance time as determined with the simulant. The fabric would be designated as "PAP 3 sec, PAB 8 sec at 1 cal/cm² sec incident energy." This system also provides flexibility for description of the incident energy in that it could be from a flame, or radiation from a source identifiable in terms other than cal/cm² sec, with the sole stipulation that the exposure pattern used be a rectangular pulse. For instance, if the source were a flame of known temperature but unknown heat flux, and a measurement

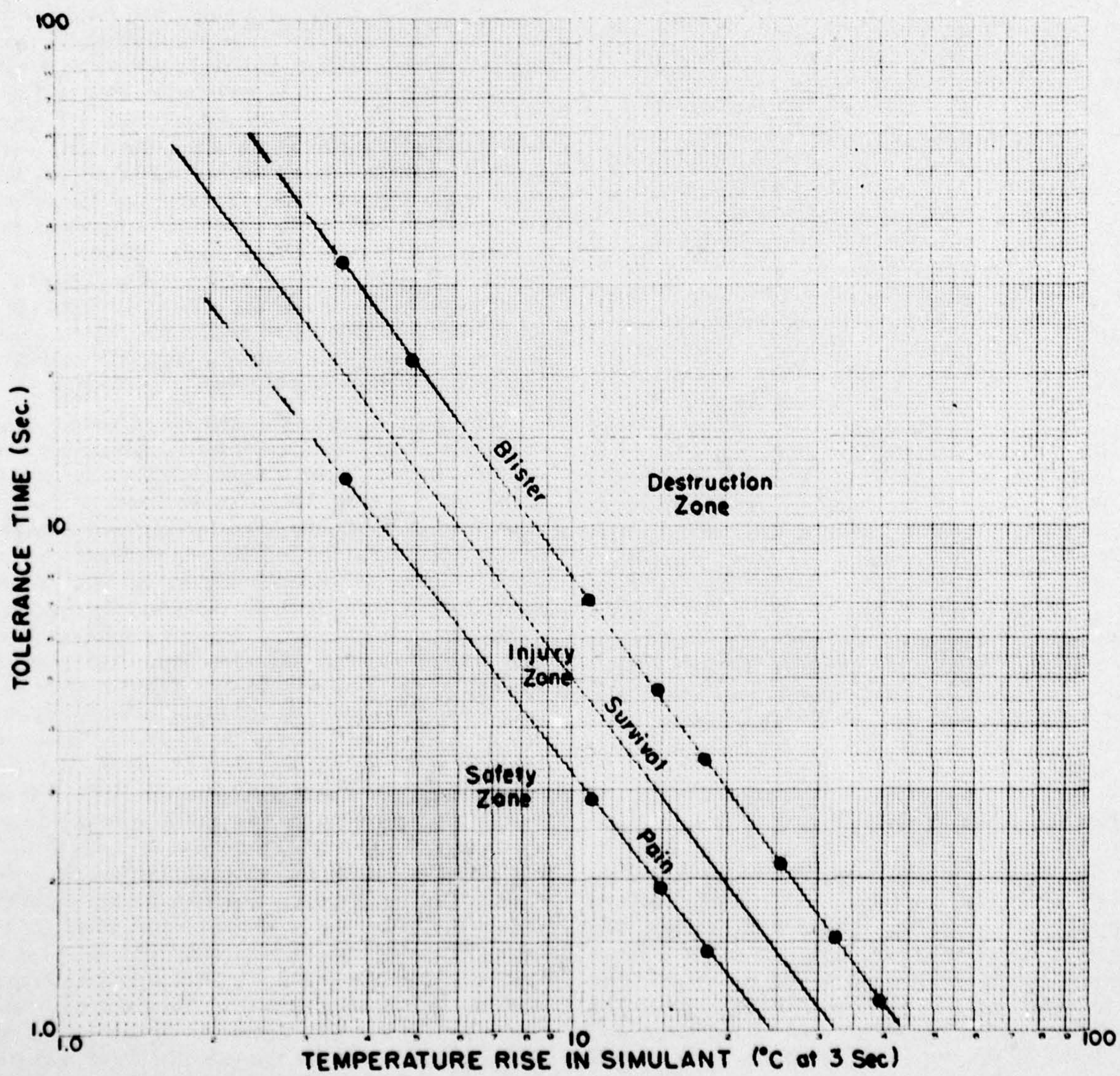

Fig. 2. Human skin tolerance time indicated by the temperature rise measured in a skin stimulant at 3 seconds' exposure to a rectangular heat pulse.

made with a calibrated receiver indicated the heat absorption rate on rectangular pulse exposure to be 0.25 cal/cm^2 sec then the rating could be expressed "PAP 3.5 sec, PAB 7 sec in contact with X°C flame." Similarly, if the source were radiant and only the color temperature known, the same data would be expressed as "PAP 3.5 sec, PAB 7 sec on radiation from X°C Source at X cm." While these terms are somewhat cumbersome they are more meaningful than any single figure such as the ratio of time to burn fabric-covered skin to the time to burn bare skin used in earlier evaluations.[14] Also, the protective capacity of the fabric would be clear to anyone reading the rating rather than to only those conversant with this experimental field. This correlation, of course, tacitly assumes that the fabric is removed immediately at the conclusion of the exposure and the skin permitted to cool in an ambient environment approximating normal room temperature. Otherwise, additional heat could flow into the skin from the fabric itself or from the surroundings causing additional damage and upsetting the empirical correlation.

Researchers and textile developers for convenience might standardize on the single figure derived from the line drawn through the mid-points between the pain threshold and blister curves, in this instance labelled "Survival" time. Physically the line represents points at which pain is produced but a blister is not; temporally it lies closer to the pain curve than to the blister curve, since the damage rate increases logarithmically with skin temperature, automatically weighting this time on the side of safety. The indicated survival time values may be compared to one another directly and such comparisons constitute a simple method of finding the best candidate of any number, the higher the value the better the protection afforded. Also, for those doing research in this area, a wealth of additional data may be presented with little additional effort. Table II illustrates these possibilities. Here are presented a sampling of fabrics which have been considered for thermal protection use arranged in order of increasing protection capacity. The weight in ounces per yard square and the color are given as the commonest identifying characteristics. The thickness is given to aid in visualizing the bulk of the fabric (if desired for research purposes the description could be further amplified with thread counts, air permeability, etc.). The data shown in this table were derived from flame contact and are simpler to appreciate than those in Table III pertaining to radiation, for few commonly-encountered flames exceed 1200°C (ca. 2200°F), while radiation exposures may vary from virtually 0 to intensities of thermonuclear magnitudes. Thus, the final three columns in Table II may be considered to be quite representative of the protection afforded against actual fire exposures and, therefore, have real meaning for the uninitiated.

Interpretation of the data in Table III should be approached with caution and might best be left to the experienced, for materials that give excellent protection at 1 cal/cm^2 sec or less may be totally inadequate in a real situation where the radiation level may be much higher. In atomic explosions levels of energy many times this magnitude are encountered, while emanations from ordinary radiation sources such as incandescent lamps and open furnaces, at a reasonable distance, commonly fall within the range of 1 cal/cm^2 sec or less. Again, the net effect of radiant exposures depends

TABLE II. PROTECTION AFFORDED FABRIC-COVERED SKIN IN CONTACT WITH FLAMES AT 1200°C

	Fabric				ΔT_{BB} °C/H	Protection Time—Flame Contact at 1 cal/cm^2 sec flux			Protection Time—Flame Contact Flame Temp = 1200°C Flux = 1.3 cal/cm^2 sec		
Log#	Material Description	Weight oz/yd^2	Thickness mm	Color	at 3 sec	Time to Pain (sec)	Time to Blister (sec)	Survival Time (sec)	Time to Pain (sec)	Time to Blister (sec)	Survival Time (sec)
42	Nomex Filament	5.00	0.250	White	20.1	1.2	2.8	1.8	<1.0	1.9	1.2
279	PBI Filament	5.00	0.253	Gold	19.6	1.3	3.0	2.0	<1.0	2.1	1.4
202b	Nomex-Staple Herringbone	3.50	0.385	Green	18.8	1.4	3.1	2.1	<1.0	2.2	1.4
202d	Nomex Staple	5.08	0.484	Green	14.0	2.0	4.9	3.0	1.4	3.1	2.0
166	Nomex Staple	4.82	0.510	Green	13.3	2.2	5.5	3.4	1.5	3.2	2.0
278	PBI Staple	5.20	0.538	Gold	13.2	2.2	5.5	3.4	1.5	3.2	2.0
171	Nomex Staple	4.85	0.568	Green	11.7	2.6	6.2	4.0	1.8	4.2	2.7
267	Cotton Simplex	10.64	0.765	White	10.2	2.8	7.0	4.2	1.9	4.5	2.9
269	Cotton Simplex	10.30	0.725	Gray	10.0	3.2	8.0	5.0	2.1	5.4	3.4
268	FR Treated Cotton Simplex	11.67	0.729	Gray	9.1	3.6	9.0	5.7	2.2	5.9	3.8
213	Nomex Staple	11.00	0.890	Green	8.4	4.1	10.5	6.4	2.8	7.5	4.9
236	Nomex Staple Knit Simplex	10.70	0.966	Green	5.2	8.0	20.5	12.5	5.5	14.0	8.8
198	Nomex Staple Puffed	8.88	0.988	Green	4.6	9.0	22.5	14.5	6.3	16.0	10.0
205	Nomex Staple & Fairtex	10.70	1.400	Green and Silver	4.1	10.0	26.0	16.0	7.0	18.0	11.2

TABLE III. PROTECTION AFFORDED FABRIC-COVERED SKIN EXPOSED TO RADIATION FROM A SOURCE AT A BRIGHTNESS TEMPERATURE OF 2300°C

	Fabric				ΔT_{ss} °C/H at		Protection Time—Radiation at 1 cal/cm² sec (T_b = 2300°C)			Irradiance (cal/cm² sec at T_b = 2300°C) Tolerable for	
Log#	Material Description	Weight oz/yd²	Thickness mm	Color	2 sec	3 sec	Time to Pain (sec)	Time to Blister (sec)	Survival Time (sec)	1 sec	3 sec
42	Nomex Filament	5.00	0.250	White	3.8	5.7	6.8	17.5	10.9	5.7	2.6
279	PBI Filament	5.00	0.253	Gold	4.8	7.2	5.0	12.5	7.9	4.5	2.0
202b	Nomex-Staple Herringbone	3.50	0.385	Green	5.5	8.2	4.2	10.6	6.6	3.9	1.8
202d	Nomex Staple	5.08	0.484	Green	4.4	6.6	5.6	14.1	8.9	4.9	2.2
166	Nomex Staple	4.82	0.510	Green	4.5	6.7	5.5	14.0	8.8	4.8	2.2
278	PBI Staple	5.20	0.538	Gold	4.4	6.6	5.6	14.1	8.9	4.9	2.2
171	Nomex Staple	4.85	0.568	Green	4.4	6.6	5.6	14.1	8.9	4.9	2.2
267	Cotton Simplex	10.64	0.765	White	2.6	3.9	11.4	30.0	18.3	8.3	3.7
269	Cotton Simplex	10.30	0.725	Gray	2.8	4.2	10.3	27.5	16.5	7.7	3.5
268	FR Treated Cotton Simplex	11.67	0.729	Gray	2.3	3.4	13.5	36.0	22.0	9.5	4.3
213	Nomex Staple	11.00	0.890	Green	2.5	3.7	12.0	32.0	19.5	8.7	3.9
236	Nomex Staple Knit Simplex	10.70	0.966	Green	2.4	3.6	12.5	33.0	20.5	9.0	4.0
198	Nomex Staple	8.88	0.988	Green	2.8	4.2	10.3	27.0	16.5	7.7	3.5
205	Nomex Staple & Fairtex	10.70	1.400	Green and Silver	2.1	3.1	15.5	40.8	25.0	10.4	4.7

heavily upon the spectral characteristics of the source and the fabric, therefore, it is always necessary to identify the radiation source used in generating any data of this kind. As used in Table III, the color or brightness temperature (T_b) is perhaps the most universally applicable and convenient means of making this identification. This information permits the user to apply black-body radiation values in calculating the heat transmission at any other brightness temperature from separate determinations of the reflectance and transmittance of the particular fabric concerned[13] and the protection time data contained in the table. It will be noted that two columns are devoted to the temperature rise in the simulated skin (ΔT_{ss}), one observed at two seconds' heating time and the other calculated for three seconds' heating time. The observation is made at 2 seconds in order to protect the simulant from overheating when high irradiances are used. The calculation (invariably at high irradiances, a linear extrapolation) to 3 seconds is used in order to render these data compatible with Figure 2. Again, times to pain and to blister and "survival" time are noted for the same fabrics as appear in Table II arranged in the same order (although the sequence no longer follows increasing protective capacity). The final columns of Table III show the intensity of radiation which may be tolerated (as determined from the "survival" time parameter) for 1 second and for 3 seconds. These data suggest that some of the fabrics would be effective in protecting against injury from thermal radiation in the nuclear weapons range. The latter area is, of course, extremely complex because of the large number of variables to be considered, e.g., weapon yield, location of detonation (ground, air, etc.), distance from detonation, atmospheric conditions, etc. For this reason any specific material under consideration would require far more extensive study. However, as a first approach this system provides a wealth of information quickly and simply. With suitable sampling it can be used to indicate directly differences due to optical properties of the fabrics. Indirectly, in conjunction with spectrophotometric measurements, the same data may be used to compute heating effects at brightness temperatures other than that of the source used during measurement. In general the radiation data are perhaps most useful as guidelines for further study of given materials while the flame-contact data provide immediate evaluations of protective capacity.

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